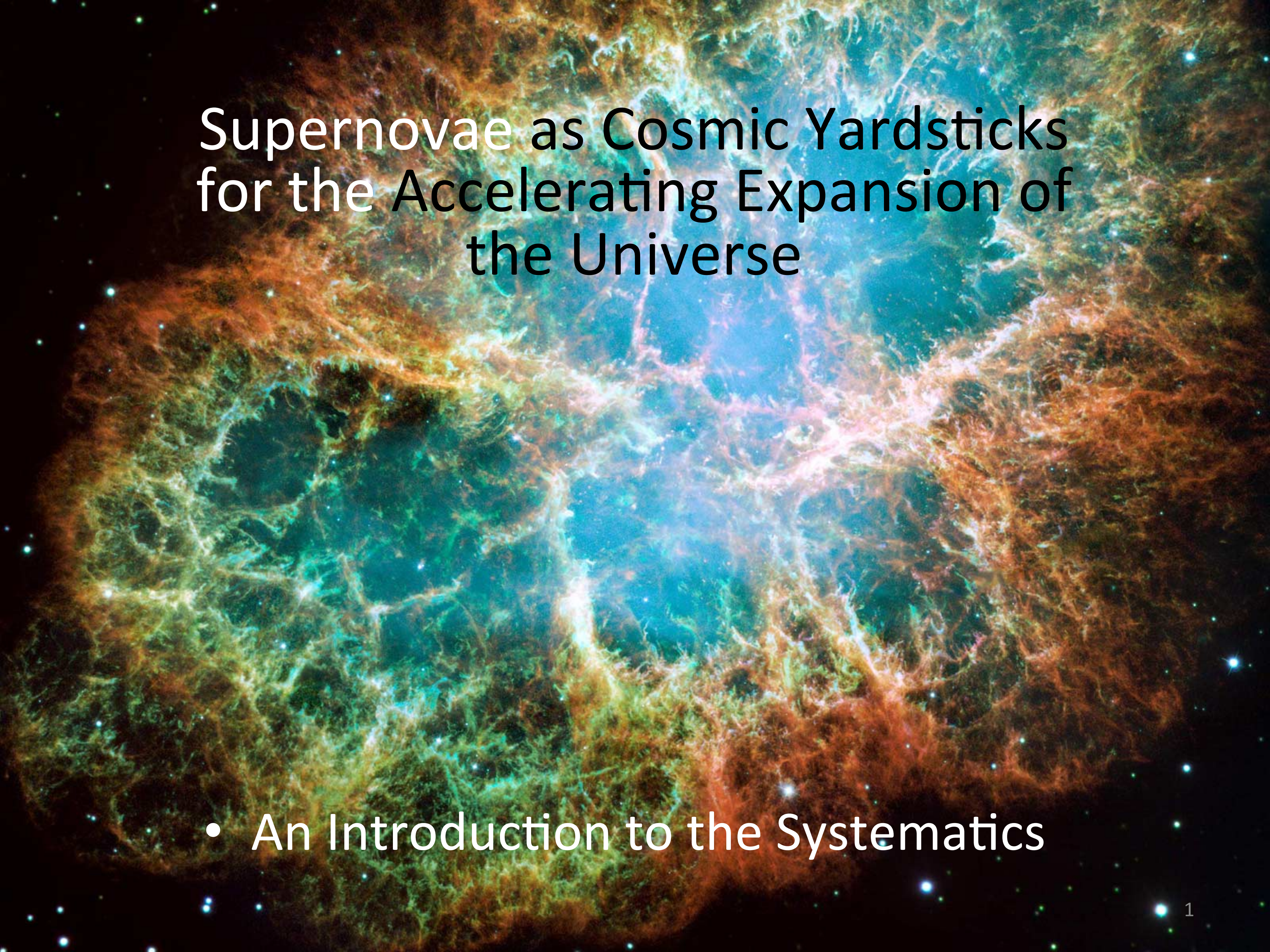


Supernovae as Cosmic Yardsticks for the Accelerating Expansion of the Universe

- An Introduction to the Systematics

Supernovae Made Simple

1) Find Supernovae

2) Determine whether they are Type Ia or not.

3) Measure their distance via Luminosity or other means.

4) Measure their distance via their redshift or the redshift of their host galaxy.

5) See which cosmology best describes the distance-distance relation.

6) Reduce systematics.

7) But first, a few words about SN taxonomy…

Supernova Taxonomy

There are several (many) type of supernovae (SN). They are distinguished by the mechanism of their collapse, and the subsequent explosion.

- SN Type I show no Hydrogen lines in their spectra
    - I-a have strong Silicon-II lines
    - I-b has no Silicon but strong He-I line
    - I-c has no Silicon or Helium
- SN Type II show strong Hydrogen lines in their spectra
    - II-b transforms with time to resemble a I-b spectrum
    - II-P has a plateau in the light curve
    - II-L has a linear decrease in magnitude versus time
    - II-n shows a variety of narrow spectral lines.

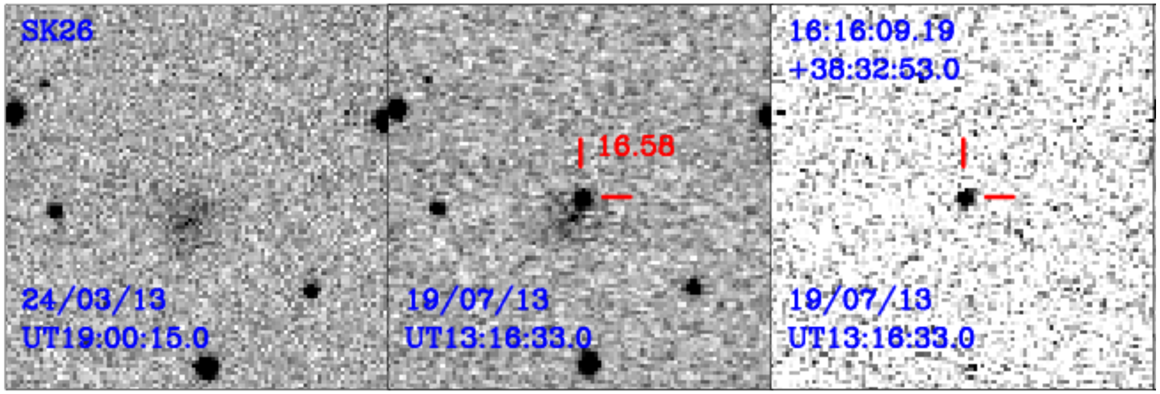
In SNIa, most of the energy expended goes into driving off the ejected shells of gas.
Typical total energy is 1.5 FOE*.

In Core Collapse SN, most of the energy goes into neutrinos.
Total energy ~100 FOE.
But the radiated energy is less than a Type Ia.
Total luminosity is dependent on the mass of the progenitor.

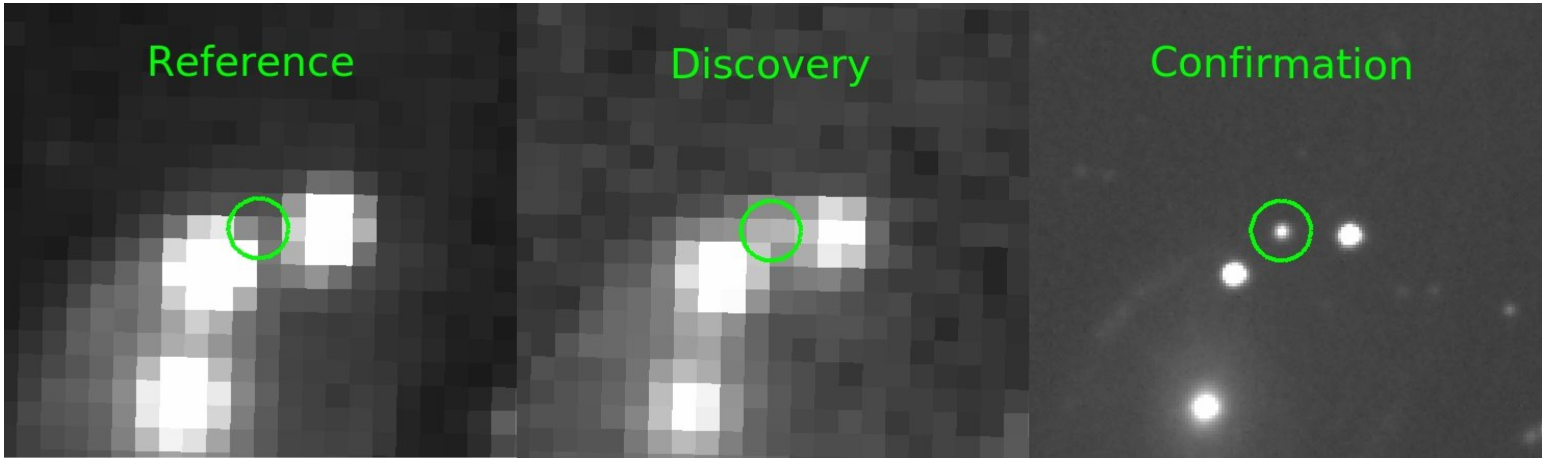
*FOE is 10^{51} ergs

Finding Supernovae

Automated
Transient
Alert
Calculates
Difference
Images
And
Compares
Residuals
To a
Threshold



Pre- and Post-SN image, along with a difference image.



Follow-up can help a lot. Especially spectroscopic follow-up.

Supernova Type Ia Tutorial

Assumption 1: All SNIa are of equal intrinsic luminosity.

A Type Ia supernova is thought to occur when one member of a binary star pair, a white dwarf star, accretes material from its partner. As the white dwarf approaches the Chandrasekhar mass (~1.38 $M_{\odot}$) it ignites Carbon fusion producing ^{56}Ni in the core, converting a significant fraction of its total mass to energy in a few seconds. This unbinds the stellar envelop, driving off ~half the gas at velocities up to 5% the speed of light.

As long as stars are not rotating rapidly, they all approach the mass limit the same way, making for equal luminosities. The absolute magnitude, M, of SNIa is typically $M = -19.3$.

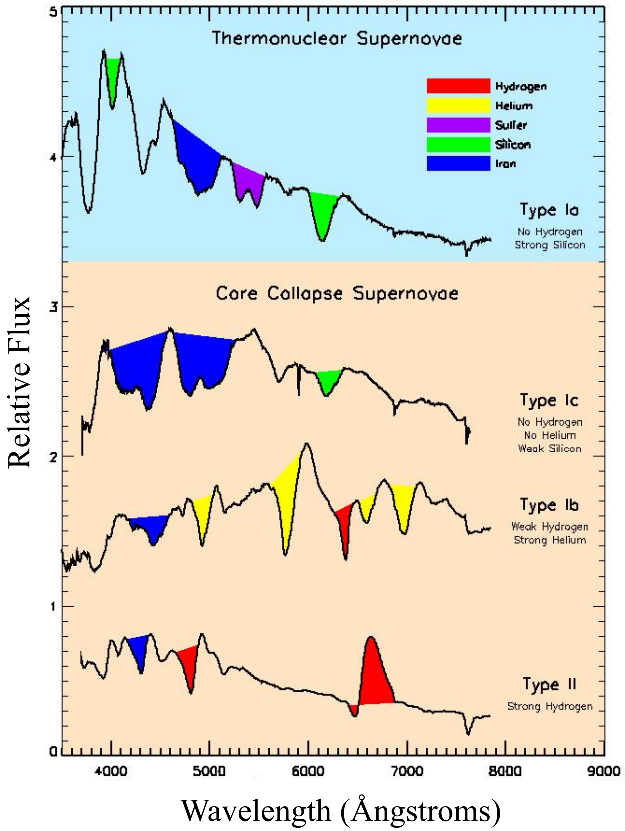
(P.S: The "absolute magnitude" M is the "apparent magnitude" at a distance of 10 parsecs.)
(P.S2: Chandrasekhar mass (1.38 $M_{\odot}$) ≠ Chandrasekhar limit (1.44 $M_{\odot}$) when stars collapse due to gravitational pressure exceeding electron degeneracy pressure.)

NB: $M \neq \mathrm{M}$

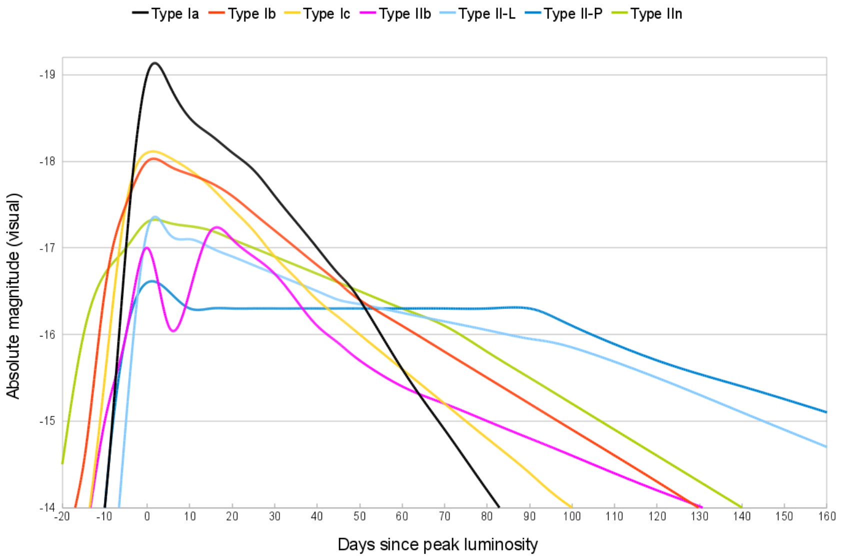
SN Typing

Supernova type is determined through two parameters:

1) Spectral content [1]



2) Rest Frame Light Curve template fitting.
B-band Peak Luminosity time sets T-Zero
Measure Rise Time
Measure Fall Time
Calculate $\Delta m_{15}(B)$



[1] Daniel Kasen, Nature, 460, 869-872 (13 August 2009).

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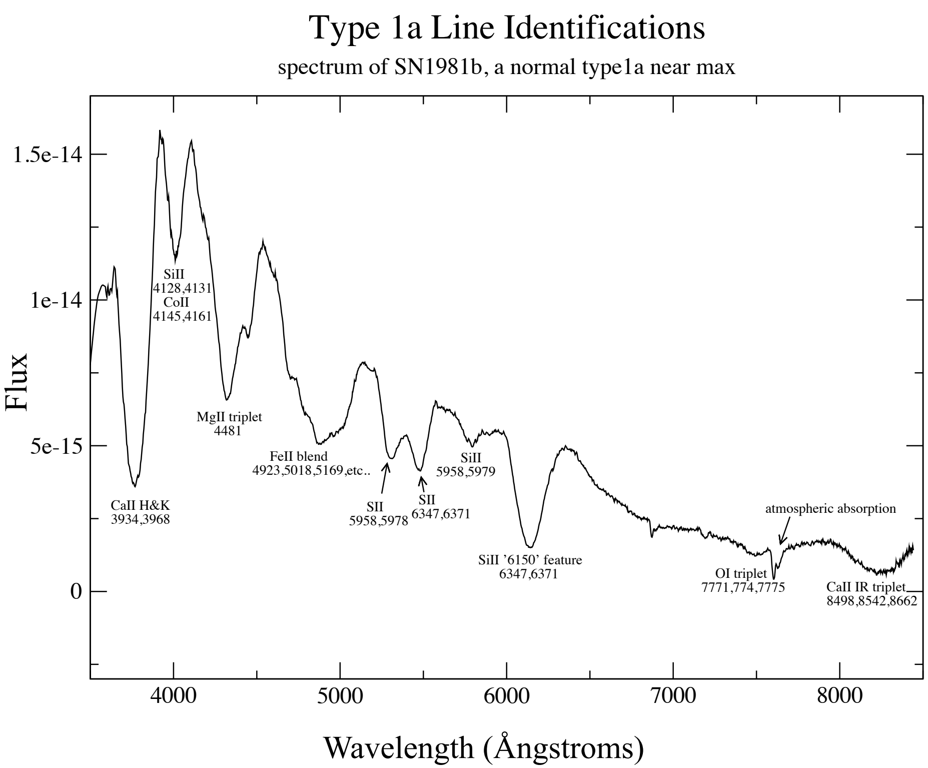
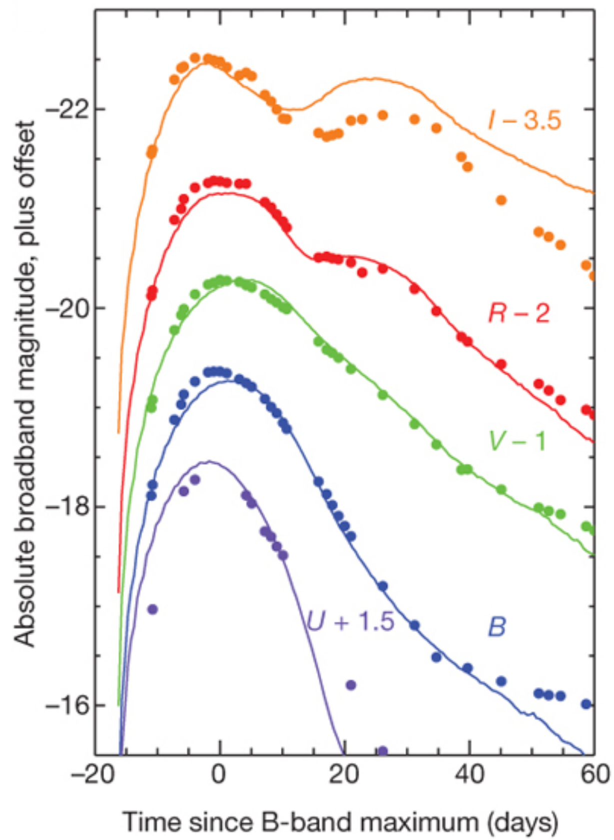


2) Light curve fitting: Compare model to data



[1] Daniel Kasen, Nature, 460, 869-872 (13 August 2009).

Light Curves

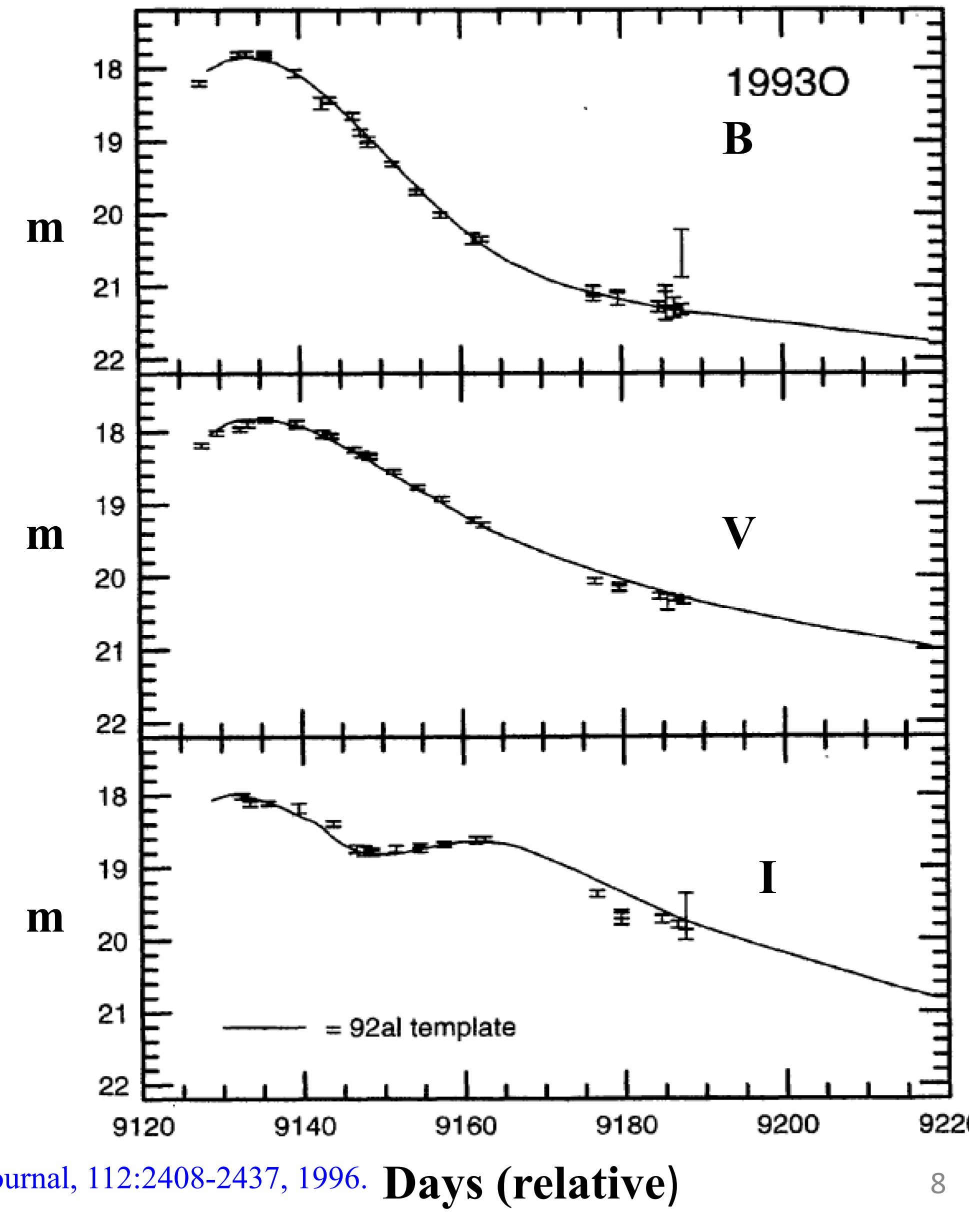
The observable emission of SNIa is powered completely by the decay of radioactive ^{56}Ni and its radioactive daughter nucleus.

^{56}Ni is synthesized in the explosion and decays by electron capture with a half-life of 6.1 days to ^{56}Co.
The cobalt decays through electron capture (81%) and β^+ decay (19%) to stable ^{56}Fe with a half-life of 77 days.

The energy release in the early phase is dominated by the down-scattering and the release of photons generated from γ-rays in the decays.

An example light curve from SN1993O taken in three filters, B, V, and I

Frequent revisits in many filters are important!

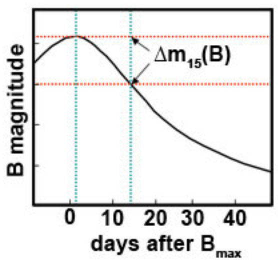


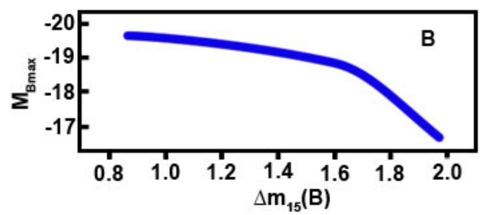
[2] Figure from Mario Hamuy *et al*., Astronomical Journal, 112:2408-2437, 1996.

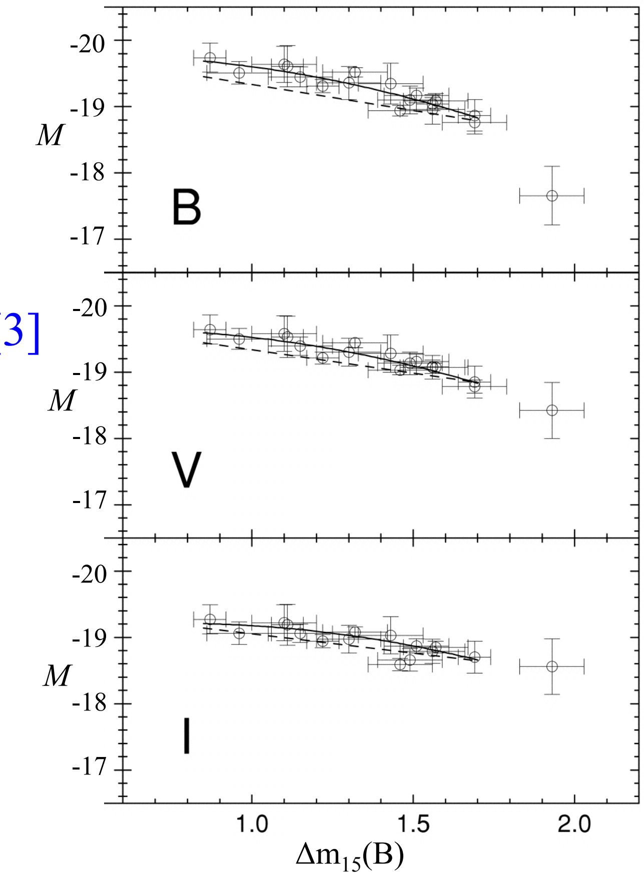
Light Curve Corrections

Three types of light curve corrections:

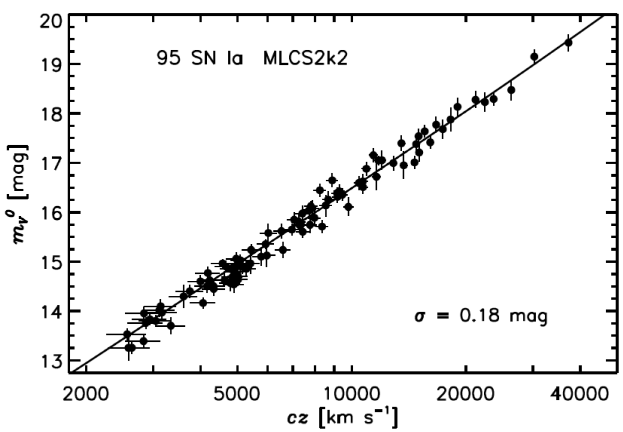
1) Luminosity Decline Rate Parameter Method, $\Delta m_{15}(B)$, removes correlation between luminosity and duration [3].







2) Multicolored Light Curve Shape Method[3]



3) Stretch Method

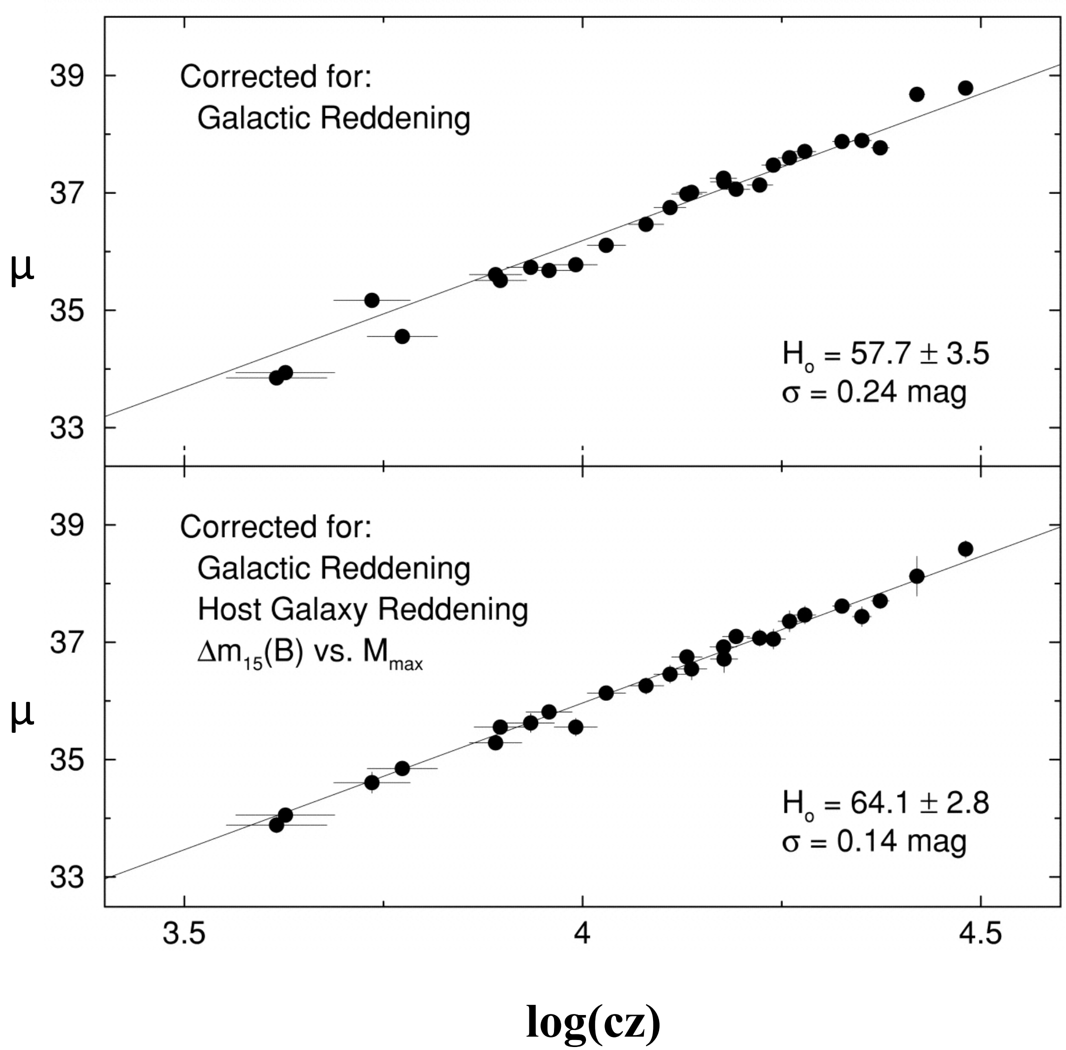
[3] M.M. Phillips *et al*., Astronomical Journal, 118:1766-1776, October 1999.
and S. Jha *et al*., Astrophysical Journal, 659:122-148, 2007.

Light Curve Corrections

There are two common corrections made to SNIa luminosities:

- Accounting for dust reddening in the host galaxy
- Removing the empirical correlation between the width of the rest-frame Light Curve, $\Delta m_{15}(B)$ and the luminosity as determined from SNIa in host galaxies whose distance is determined using Cepheid variable stars.

The resulting corrected luminosity shows much lower dispersion.



[4] Figure from M.M.Phillips *et al*., Astronomical Journal, 118:1766-1776, 1999.

Supernova samples

In the LSST era, we expect to observe ~500 SN per night. But LSST does not have a spectrograph. We will have to make use of photometric redshift determinations if we expect to benefit from these events.

In 1998, Adam Riess stated:

> "Confidence in these results (observing the accelerating expansion of the universe) depends not on increasing the sample size but on improving our understanding of systematic uncertainties." [5]

He had 16 SN!?!...

What are the primary sources of systematic uncertainty when using SN as cosmological yardsticks?

[5] Adam Riess et al., Astronomical Journal, 116: 1009-1038, September 1998.

Supernova samples

LSST will send out Transient Alerts within 1 minute of the image passing through the DM pipeline.

Special purpose telescopes will do follow-up on a select subset (<3%) of the SN population. GMACS/MANIFEST spectrograph at the Giant Magellan Telescope, and OPTIMOS spectrograph at the European Extremely Large Telescope are proposed for spectrometric red-shift measurements. At best we can expect a few per cent of the SN candidates will have resolved spectra. The rest will be analyzed with photometric red-shift determinations (photo-z).

How well can we map out the color-redshift relationship?
How large a training dataset do we need?
How well can we constrain the z-dependence of the relationship?

Using SNIa as standard candles

Assumption 2: SNIa luminosity falls off as $1/R^2$.

Define the "distance modulus" $\mu = m - M$, where m is the apparent magnitude, and M is the absolute magnitude, $M = -19.3$ for SNIa.

We can determine the distance to any particular SNIa from its apparent luminosity. So μ is a proxy for the luminosity distance, d_L, to the SNIa:

$$d_L = 10^{(\mu/5)+1}$$

in units of parsecs.

$$\delta d_L/d_L = 0.461\ \delta\mu = 0.461 \sqrt{(\delta m^2 + \delta M^2)}$$

What do we know about δm and δM?

δM is the intrinsic variability of SNIa, and has been measured for nearby SNIa ($z < 0.15$).

δm is includes telescope effects, and dust-related effects.

Hubble distance

Assumption 3: The recession velocity of SNIa can be used to determine its distance.

The recession velocity of SNIa are determined typically from their redshifts, z,

$$z = \lambda_o/\lambda_r - 1$$

where λ_o is the observed wavelength of some spectral feature, and λ_r is the wavelength at rest. The spectral feature can be from the SNIa or from the host galaxy, if it can be identified.

The redshift gives the recession velocity, $\beta = v/c$, from

$$z + 1 = \sqrt{(1+\beta)/(1-\beta)} \qquad \text{or equivalently}$$

$$\beta = (1-a^2)/(1+a^2) \qquad \text{where } a = 1/(1+z) \text{ is the scale factor}$$

The Hubble relation gives us the distance to the SNIa, d_H, from the measured recession velocity:

$$d_H = \beta c/H_0$$

assuming we know the Hubble constant, H_0 ~= 67.80 ± 0.77 km/s/Mpc[6].

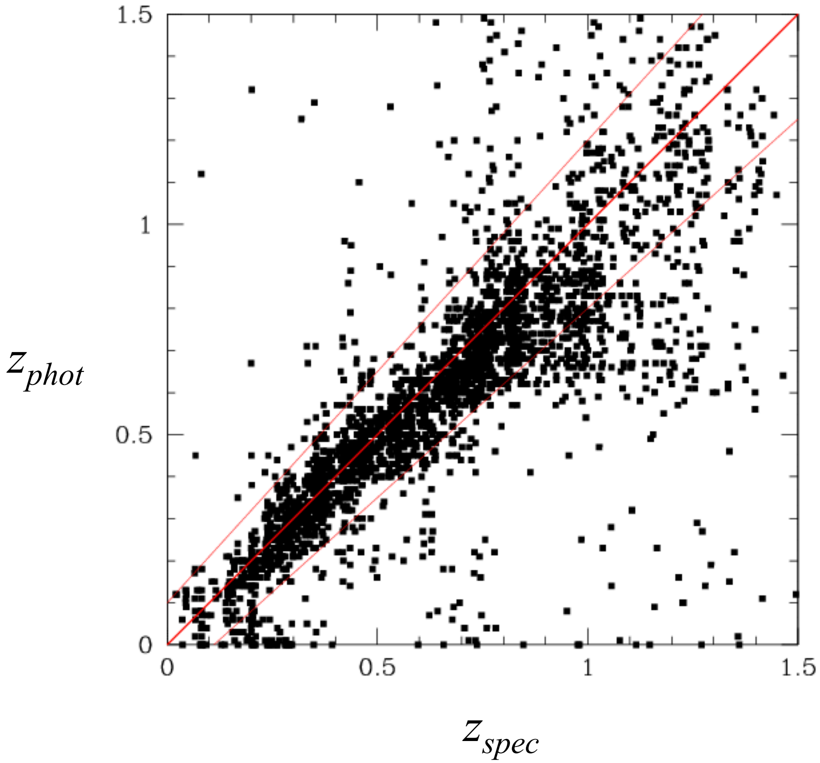
[6] http://arxiv.org/abs/1303.5062, Planck 2013 results. I. Overview of products and scientific results

Photometric vs Spectrographic Redshift

There are major difficulties encountered when relying on photometric redshift measurements for distance calculations.

A comparison of photo-zs vs spectro-zs shows a large dispersion, with a significant fraction of catastrophic failures.

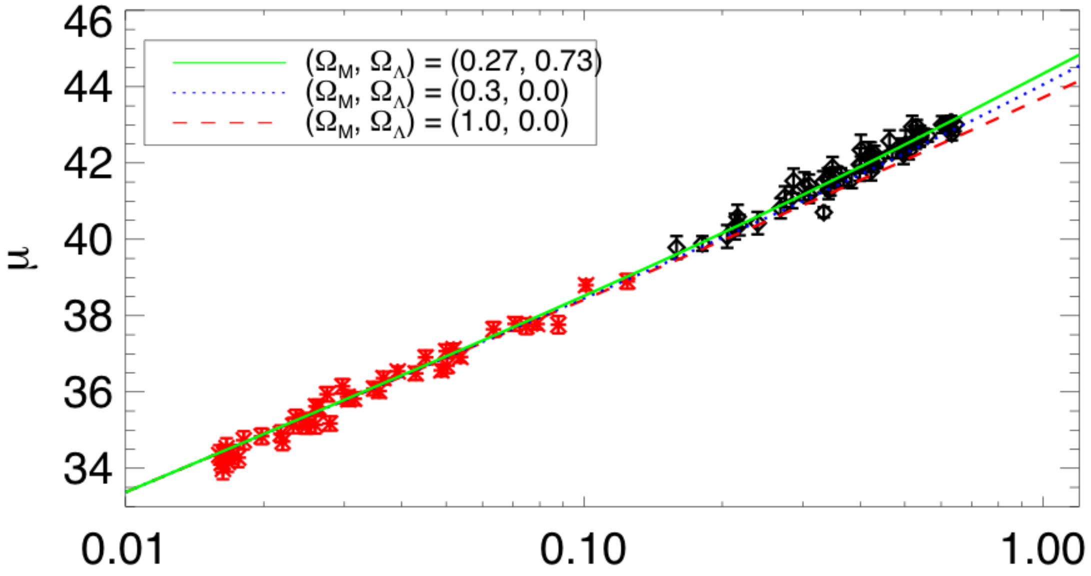
Current planning anticipates using the LSST Deep Drilling Fields only for Supernova Science.



[7] From CFHTLS

Distance vs Distance?

So now we have two different measures for the distance to the SNIa; one based on $1/R^2$ luminosity and the other based on redshift from the Hubble expansion.



Redshift z

[8] Adapted from Woods-Vasey, *et al*., Astrophysical Journal, 763:88 (1 February 2013).

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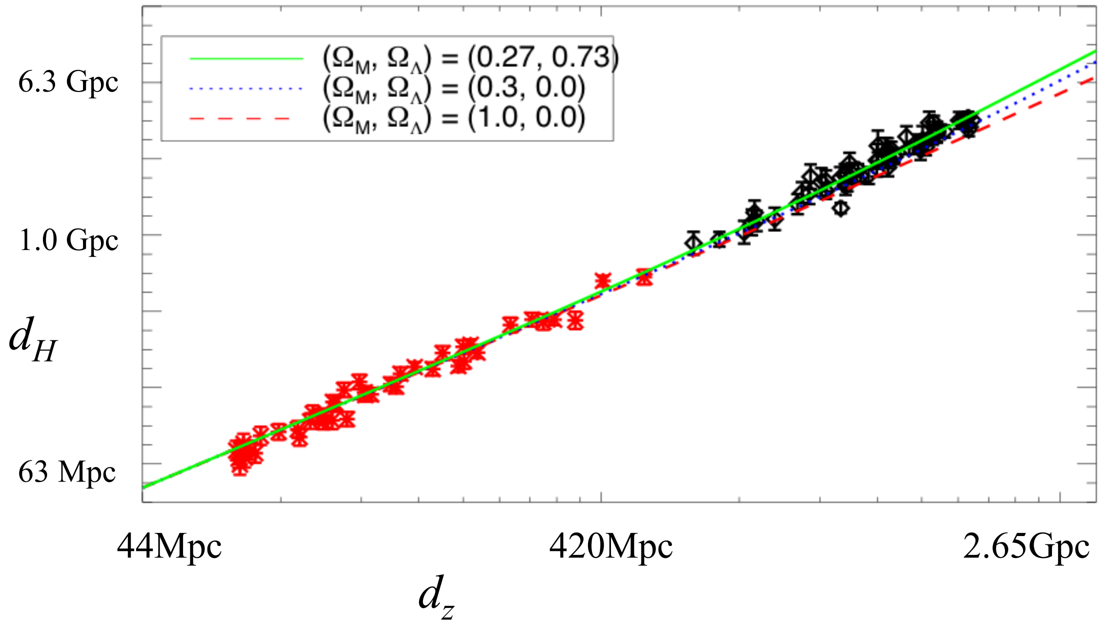
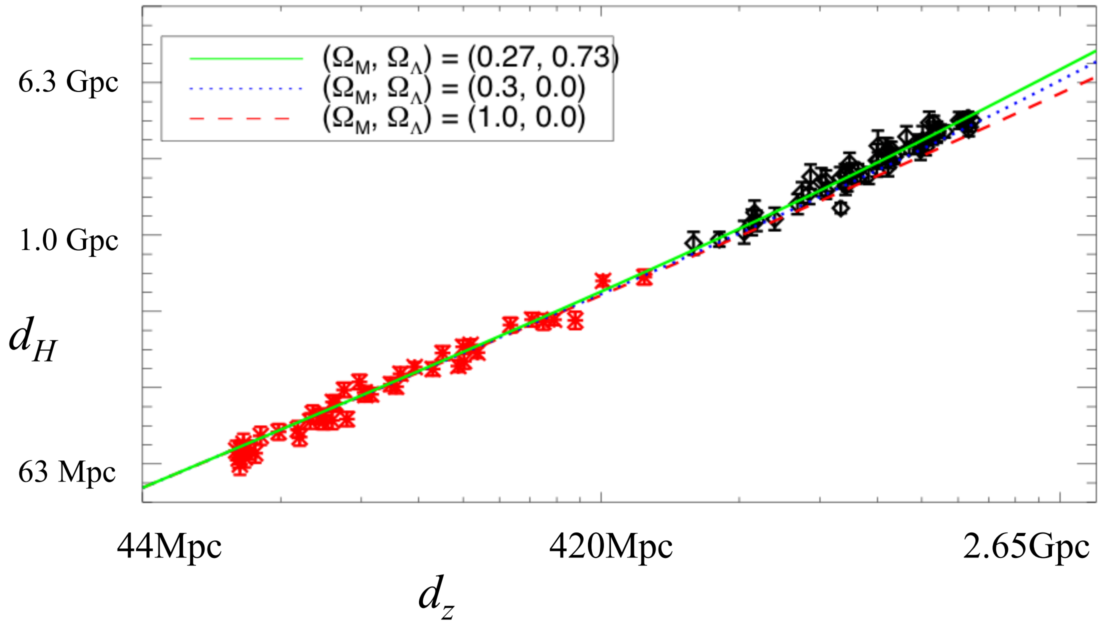


[8] Adapted from Woods-Vasey, *et al*., Astrophysical Journal, 763:88 (1 February 2013).

Extracting Cosmology

In one model, assuming a spatially flat universe

$$H(z) = H_0 \left(\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}\right)^{½}$$



[8] Adapted from Woods-Vasey, *et al*., Astrophysical Journal, 763:88 (1 February 2013).

Where are the uncertainties?

Absolute luminosity $M = -19.30 \pm 0.08$ [9]

- Rotation/Magnetic effects, M > 2.58 $M_\odot$ [10].
- Correlated with Light Curve Shape, can be accounted for.
- Stellar mergers, M ≈ 2$M_\odot$
- Uncorrelated intrinsic variability.
- Misidentification of SN Type.

Other luminosity corrections

- Dust, and other color corrections, can be measured and bounded. But the *z*-dependence is not well known.

Photometric redshift determination

- Can we measure a large enough training set to give us a good unbiased sample of spectrographic redshift SNIa?

[9] R. Kessler et al., Astrophysical Journal Supplement Series, 185:32-84 (November 2009).
[10] http://arxiv.org/abs/1301.5965, New mass limit for white dwarfs, U. Das and B. Mukhopadhyay.

Backup

Supernova Taxonomy

There are several (many) type of supernovae. They are distinguished by the mechanism of their collapse, and the subsequent explosion.

- Type I show no Hydrogen lines in their spectra
  - I-a have strong Silicon-II lines
  - I-b has no Silicon but strong He-I line
  - I-c has no Silicon or Helium
- Type II show strong Hydrogen lines in their spectra
  - II-b transforms with time to resemble a I-b spectrum
  - II-P has a plateau in the light curve
  - II-L has a linear decrease in magnitude versus time
  - II-n shows a variety of narrow spectral lines.

SN Type	**Mass (in $M_{\odot}$)**	**Mechanism**	**Peak Luminosity**
Ia	1.38	Carbon fusion	-19
Ib	>40	Fe core collapse	-17
Ic	>40	Fe core collapse	-16 to -22
II-b	25-40	Fe core collapse	-17
II-L	25-40	Fe core collapse	-17
II-P	8-10	Electron capture	-14
II-P	10-40	Fe core collapse	-16
II-n		? May be Ia ?	-22